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Fibre-bridged fatigue delamination in multidirectional composite laminates

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Abstract:

The influence of fibre bridging on delamination failure in multidirectional composite laminates with different thickness scales is characterized, and the dependence of fibre bridging significance on laminate thickness as well as loading regime is investigated in this paper. Both quasi-static and fatigue resistance curves (*R*-curve) are experimentally determined to quantify the significance of fibre bridging in delamination growth. The results clearly demonstrate that thickness has effect on the amount of fibre bridging in quasi-static delamination. And the significance of fibre bridging decreases with the increase in laminate thickness. However, the situation for fatigue delamination growth (FDG) is much more complicated. The difference in fibre bridging generation seems to be insignificant in short fatigue cracks and at the plateau state, whereas more bridging fibres can be present in a thinner laminate in-between state. Loading regimes also have significant effect on the amount of fibre bridging. The results clearly demonstrate that more bridging fibres can be generated in quasi-static delamination compared to fatigue. A modified Paris relation proposed by the authors in previous studies is employed in present study to determine fibre-bridged FDG behaviors in multidirectional composite laminates with various thickness scales. All fatigue data locate in a relatively narrow band region of the resistance graph, resulting in a master resistance curve in determining fatigue delamination behaviors. This clearly demonstrates that neither thickness nor fibre bridging has significant effect on fatigue delamination behaviors, if the similarity is well represented.

Keywords: B. Fatigue; B. Delamination; Multidirectional; A. Polymer-matrix composites (PMCs)

1. Introduction

Advanced composite materials have been widely used in aerospace engineering as a result of their excellent mechanical performance and weight-saving potential. However, composite laminates are susceptible to delamination, a typical damage evolution usually observed between neighboring layers. This kind of damage can be introduced into a composite structure via stress concentration, low velocity impact, manufacturing defects and so on. Furthermore, it can gradually propagate under fatigue loading and has the potential to cause failure of a composite structure. As a result, increasing attentions have been focused on delamination growth under fatigue loading [1-9]. And various power relations, in terms of fatigue crack growth rate *da/dN* against the maximum strain energy release rate (*SERR*) [3,5], the *SERR* range [6], combinations of them [7,8], or other forms [1,2,9], have been proposed to characterize fatigue delamination behaviors.

Fibre bridging is an important shielding phenomenon frequently observed during delamination growth of some kind of composite laminates. The presence of these bridging fibres, in the wake of a crack front, can significantly affect interlaminar resistance according to quasi-static delamination studies [10-12]. Particularly, the *R*-curve, in terms of delamination resistance G_{IC} against crack extension a-a_0, and the bridging law, in terms of bridging stress σ_{br} against crack opening displacement δ, are two effective methods usually applied to evaluate the significance of fibre bridging in quasi-static delamination growth tests. The more bridging fibres generated in delamination growth tests can result in a higher magnitude of the *R*-curve and the bridging stress. Experimental methods used to determine the *R*-curve as well as the bridging stress distribution have been gradually established [10-13] and numerical models based on these concepts have been developed to predict fibre-bridged quasi-static delamination growth in composite laminates [14-16].

In contrast to quasi-static studies, not enough attention has been paid into the effect of fibre bridging on delamination growth under fatigue loading. Hojo et al [17] investigated the effects of fibre bridging on FDG via a G_{max}-constant test program. Significant retardation effect was observed during FDG because of fibre bridging.

Murri [18] gave a thorough discussion on data reduction in fibre-bridged FDG, where she suggested that "in order to be useful in structural modeling, expressions relating the fatigue delamination growth rate and *SERR* must be corrected for the effects of fibre bridging". In [18], both the Paris relation and the normalized Paris relation (G_{max} was normalized with quasi-static *R*-curve) were employed to determine FDG. Shivakumar et al [19] also used the *R*-curve from quasi-static tests to normalize the *SERR* in fatigue delamination, in order to develop an empirical total fatigue model. However, it should be stressed that there was evidence that the amount of fibre bridging in FDG was not the same to that in quasi-static delamination [11,20]. As a result, it is not correct to directly use quasi-static results to normalize fatigue data. Thus, in another study [21], a compliance method was introduced to make a correlation between quasi-static and fatigue delamination resistance. And a normalized Paris relation based on this correlation was developed to determine FDG. Gregory et al [22] employed the bridging law to quantify fibre bridging in fatigue delamination and proposed a new power law relation to explore the effects of temperature on FDG. The application of this new model in fatigue delamination analysis can significantly reduce data scatter. As a result, the effects of temperature on FDG were well explored. The concept of bridging law has been also applied by other researchers [11,23-24]. All these studies indicate the *SERR* applied on crack front seems a reasonable parameter in representing the similitude in fibre-bridged fatigue crack growth. The same conclusion was also made by Yao et al [25,26], via energy dissipation analysis and damage mechanism examinations on fibre-bridged FDG.

Accordingly, a modified Paris relation has been proposed to appropriately explore fibre-bridged fatigue delamination behaviors [26].

According to above studies [17-26], fibre bridging has significant retardation effects on FDG behaviors. In line with quasi-static studies [10,12,20,21], it would appear that a series of factors can affect the significance of fibre bridging in delamination growth, viz. ply orientation, thickness dimension, mixed-mode ratio and so on. However, to the best knowledge of the authors, little attention has been given to studying the effects that these parameters have on fatigue delamination. In a study completed by Peng et al [21], it was reported that the same or similar amount of fibre bridging can be present in quasi-static and fatigue delamination. However, a different conclusion was made by other researchers [11,21]. Particularly, Stutz et al [11] provided a semi-experimental method to quantify the bridging stress distributions in both quasi-static and fatigue delamination. The determined bridging stress in quasi-static delamination was higher than that observed in fatigue, indicating that more fibre bridging can be generated under quasi-static loading. Obvious differences in the amount of fibre bridging in quasi-static and fatigue delamination were also observed in an experimental study conducted by Yao et al [20]. Furthermore, it was recently reported that the significance of fibre bridging in fatigue delamination was dependent on stress ratio [27]. More fibre bridging can be present in a higher stress ratio fatigue delamination. In the authors' opinion, it is, therefore, necessary to explore the effects of these relevant factors on the significance of fibre bridging as well as the corresponding fatigue delamination behaviors in composite laminates, which can benefit in-depth understanding on fibre-bridged fatigue delamination behaviors.

The first aim of this paper is therefore to investigate the significance of fibre bridging in delamination growth of multidirectional composite laminates with different thickness scales under quasi-static and fatigue loading. Particularly, the effects of thickness and loading regime (i.e. quasi-static loading vs. fatigue loading) on the amount of fibre bridging are investigated via the experimentally determined *R*-curves. The second objective is to explore fibre-bridged fatigue delamination behaviors in multidirectional composite laminates with different thicknesses. Particularly, both the Paris and the modified Paris relations are employed in fatigue data reduction.

2. Material and experiments

2.1 DCB specimen preparation

To investigate the significance of fibre bridging in quasi-static and fatigue delamination in multidirectional composite laminates with different thickness scales, DCB specimens with ±45//∓45 (// indicates the delamination plane) ply orientation were designed. According to previous studies [20], three factors, such as crack jumping, residual thermal stress and non-uniform *SERR* distribution around crack front, were carefully taken into account in the layup sequence design. As a result, the stacking sequences were designed as $[(\pm45/0_{12}/\mp45)//(\pm45/0_{12}/\mp45)]$ for 32-Layer with a nominal cured thickness of h=5.0mm, and $[(\pm45/0_{20}/\mp45)//(\pm45/0_{20}/\mp45)]$ for 48-Layer with a nominal cured thickness of h=7.5mm.

Multidirectional composite laminates were fabricated via hand lay-up process using prepreg made from unidirectional, continuous carbon-fibres in a thermosetting epoxy matrix (‘M30SC/DT120’ supplied by Delta-Tech S.p.A., Italy). A 12.7μm Teflon film was inserted in the middle plane of these laminates during the hand lay-up process to act as an initial delamination, of typically a_0=60mm. The laminates were cured in vacuum in an autoclave at a pressure of 6 bars and temperature of 120℃ for 90 minutes, according to the material supplier’s recommendation. After curing, all laminates were C-scanned to detect potential imperfections and they were subsequently cut into 25mm width beams with 200mm length. A pair of aluminum loading blocks, 25mm width by 20mm length with 6mm thickness, was adhesively bonded onto the specimen at the side of the Teflon insert for load introduction.

One side of the DCB specimen was coated with a thin typewriter correlation fluid to enhance visibility of the crack front during the tests. And a strip of grid paper was pasted on the specimen coated side to aid in measuring crack propagation length.

2.2 Quasi-static and fatigue experiment procedures

Three DCB specimens of each thickness were quasi-statically tested to determine interlaminar resistance according to the ASTM D5528-01 standard. These tests were conducted on a 20kN Zwick machine under displacement control with an applied displacement rate 1.0mm/min. A digital camera system was used to monitor crack propagation via automatically recording an image of the specimen edge every 5 seconds. The quasi-static experimental setup is illustrated in Fig.1(a).

All fatigue experiments were conducted on a 10kN MTS servo-hydraulic test machine under displacement control at a frequency of 5Hz and with a stress ratio R=0.5 in ambient conditions. The same digital camera system was used to monitor fatigue crack propagation at the maximum displacement with pre-defined intervals during the tests. The force, displacement and fatigue cycle number were automatically stored in an Excel file every 100 cycles, enabling data evaluation after the tests. The fatigue experimental setup is illustrated in Fig.1(b).

According to our previous experimental experience in this field [25,26,29], a special test procedure was programed to determine fatigue delamination with different amounts of fibre bridging. DCB specimens were repeatedly tested for several times with different pre-crack lengths, but keeping *R*-ratio the same. Particularly, FDG rate continuously decreased with crack propagation in a displacement controlled test and this fatigue test was manually terminated in case of crack retardation to reduce test duration. After this fatigue test, a monotonic loading-unloading cycle was performed on the specimen until the load-displacement curve became nonlinear. According to this cycle, both interlaminar resistance of a given fatigue crack length and the applied displacements for the subsequent fatigue test can be appropriately determined. Afterwards, a subsequent fatigue test was continued on the same specimen with increased displacements. This sequence was repeated several times until the maximum displacement capacity of the test machine was reached.

2.3 Data reduction methods

The modified compliance calibration (MCC) method, recommended in the ASTM D5528-01 standard, was employed to calculate the *SERR* in quasi-static and fatigue delamination. The 7-point Incremental Polynomial Method, recommended in the ASTM E647-00 standard, was used to determine the FDG rate *da/dN*.

3. Fatigue delamination models

Among various methods, the Paris type relations, based on the fracture mechanics, have been widely used in fatigue delamination studies [4]. In these relations, fatigue crack growth *da/dN* is usually correlated to the fracture mechanics parameters, such as *K* for metals or *G* for composites. And a typical Paris power law relation is given as Eq.(1). According to previous studies [20,27], the use of this relation was an effective way to qualitatively evaluate the significance of fibre bridging in fatigue delamination in composite laminates.

$$\frac{da}{dN} = C\left(\Delta\sqrt{G}\right)^n = C\left[\left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2\right]^n \tag{1}$$

where G_{max} and G_{min} are the maximum and minimum *SERR*s in a fatigue cycle; *C* and *n* are curve-fitting parameters of the Paris relation.

One should note that there is no consensus on the similitude parameter in fatigue delamination studies, leading to variations in the Paris relations. The use of an appropriate similitude parameter can promote one's understanding on FDG, and vice versa [6]. For fibre-bridged fatigue delamination, a modified Paris relation with a new similitude parameter $\Delta\sqrt{G_{eff}}$, see Eq.(2), has been proposed in a recent study [26]. There is evidence that the application of this new power law relation can result in appropriately interpreting fibre-bridged fatigue delamination behaviors in composite laminates and significantly benefiting one's in-depth understanding on this phenomenon [26,29].

$$\frac{da}{dN} = C_1\left(\Delta\sqrt{G_{eff}}\right)^{n_1} = C_1\left[\frac{G_0}{G_{IC}(a-a_0)}\Delta\sqrt{G}\right]^{n_1} \tag{2}$$

where $G_{IC}(a\text{-}a_0)$ represents delamination resistance increase because of fibre bridging;

G_0 is the intrinsic delamination resistance without fibre bridging; C_1 and n_1 are curve-fitting parameters of the modified Paris relation.

Both the Paris and the modified Paris relations are employed in present study. Particularly, the traditional Paris law, see Eq.(1), is used to highlight the influence of the thickness and loading regime on the significance of fibre bridging in fatigue delamination. Whereas, the modified Paris relation, see Eq.(2), is used to appropriately explore fibre-bridged fatigue delamination behaviors in multidirectional composite laminates with different thickness scales.

4 Results and discussion

4.1 Quasi-static delamination growth

For each laminate thickness, three DCB specimens were tested so as to determine interlaminar resistance under quasi-static loading. Significant fibre bridging was observed in the wake of a crack front during delamination growth. These bridging fibres can release stress concentration around crack front and enhance interlaminar resistance. And fibre bridging develops with crack propagation, making the increase in delamination resistance.

Fig.2 summarizes all quasi-static data from DCB specimens with different thickness scales in terms of interlaminar resistance G_{IC} against crack extension a-a_0, i.e. quasi-static *R*-curve. Apparently, the magnitude of *R*-curve is not the same during delamination growth. It initially increases from the similar values (i.e. 251.36J/m^2 for 32-Layer and 215.34J/m^2 for 48-Layer) with crack propagation and finally becomes constant (i.e. 1247.96 J/m^2 for 32-Layer and 975.56 J/m^2 for 48-Layer) after extensive crack growth. The resistance increase is even more rapid and significant in a thinner laminate compared to that in a thicker laminate. As the presence of fibre bridging is the main reason for the resistance increase [10-13], it is, therefore, reasonable to conclude that more bridging fibres can be generated in delamination of thinner multidirectional composite laminates.

To further understand the resistance increase shown in Fig.2, post-mortem fractography examinations were conducted to explore the associated damage mechanisms in quasi-static delamination growth. Fig.3 provides the delamination profiles of composite laminates with different thickness scales. For 32-Layer, obvious zig-zag crack is observed in some locations, whereas this feature is significantly reduced with thickness increase, due to the increase in laminate bending stiffness [28]. In our understanding, the presence of zig-zag profile can cause difference in the real crack propagation scale and the measured crack length (i.e. the projected crack length), which is even obvious in 32-Layer as illustrated in Fig.3(a). With a careful calculation, this difference is around 10%. If we take this difference into account, the initial delamination resistance of 32-Layer is almost the same to that of 48-Layer (228.52J/m^2 vs. 215.34J/m^2). However, even if we take this length difference into account, there is still obvious difference in the resistance increase during crack propagation, especially at the plateau stage, which mainly attributes to the difference in fibre bridging generation. In other words, more bridging fibres can be appeared in delamination of 32-Layer. In our understanding, the zig-zag crack profile can promote more fibre bridging in delamination growth.

Fig.4 provides SEM results associated with the fracture surfaces at both the onset and the crack propagation stages for the multidirectional composite laminates tested, so as to have better understanding on the phenomenon observed in Fig.2. At the beginning of a delamination growth, fibre print is the dominant microscopic feature located on fracture surfaces, and the surfaces of naked fibres look really smooth and clean, without any matrix debris bonded or left on them. This indicates that the fibre/matrix interface is the weak point in delamination of this kind of composite material. As a result, fibre/matrix debonding is the dominant damage mechanism at the initial crack growth. With crack propagation, besides fibre prints, hackles are also observed in some locations and the fracture surface becomes rougher compared to the onset of crack growth. One should note that hackles are a typical microscopic feature frequently observed in mode II and mixed-mode I/II delamination growth because of the shear stress. Its appearance in mode I delamination mainly attributes to fibre pulled out from the surrounded matrix, as a local shear stress state can exist during this pullout procedure. If one takes a closer look at this microscopic feature, it is in an even larger scale on the fracture surface of 32-Layer, indicating more fibres can be pulled out from matrix during delamination growth (i.e. more fibre bridging generation).

Accordingly, thickness has effects on the crack propagation profile as well as the delamination behaviors. The appearance of a zig-zag crack profile can promote fibre bridging generation. As a result, more bridging fibres can be present in quasi-static delamination of a thinner laminate, contributing to more significant increase in interlaminar resistance as illustrated in Fig.2 of the 32-Layer.

4.2 Fatigue delamination growth

Two 32-Layer DCB specimens, termed as Sp-32-01 and Sp-32-02, and one 48-Layer DCB specimen, termed as Sp-48, were repeatedly tested with different fatigue pre-crack extensions, i.e. different amounts of fibre bridging. Both the *R*-curve and the Paris relation, see Eq.(1), were applied to investigate the significance of fibre bridging in FDG. The modified Paris relation, see Eq.(2), was subsequently employed to examine the effects of thickness and fibre bridging on FDG in these multidirectional composite laminates.

4.2.1 Fibre bridging significance in fatigue delamination

Interlaminar resistance at several fatigue delamination intervals was experimentally determined via the test procedure introduced in Section 2.2. Fig.5 summarizes all results in terms of G_{IC} against a-a_0. For both thicknesses, delamination resistance increases with crack propagation. Particularly, there is a linear increase for 32-Layer, whereas a nonlinear increase is observed for 48-Layer. The resistance increase can be accurately determined via Eq.(3) and Eq.(4), respectively. Interestingly, resistance increase rate is much steeper for 32-Layer compared to 48-Layer, which is similar to the quasi-static results illustrated in Fig.2. Taking a closer look at these results, one should note that the magnitudes of resistance at the short fatigue delamination (i.e. a-a_0 is around less than 25.0mm) are similar for both thicknesses. With crack propagation, delamination resistance in 32-Layer laminates is much larger than that in 48-Layer, due to the higher resistance increase rate (i.e. a faster fibre bridging development). However, delamination resistance of both laminates finally becomes the same after fibre bridging has been fully developed. A fractography analysis demonstrates that the zig-zag crack profile observed in quasi-static delamination of 32-Layer is significantly reduced in FDG, as illustrated in Fig.6. This means that loading regimes have effects on the delamination behaviors (i.e. damage mechanisms), and subsequently affect the significance of fibre bridging. As fibre bridging is still observed in fatigue delamination, one can therefore make the following important conclusions: (a) the significance of fibre bridging in short fatigue delamination and at the plateau state seems to be independent of laminate thickness; (b) the significance of fibre bridging in-between state is dependent of laminate thickness, and more fibre bridging is present in fatigue delamination of a thinner laminate; (c) the rate of fibre bridging development is related to laminate thickness, particularly, it develops more rapidly in a thinner laminate; (d) the scale of fibre bridging region depends on laminate thickness, and it is much larger for a thicker laminate in both quasi-static and fatigue delamination.

$$G_{IC} = 161.42 + 20.95(a - a_0) \tag{3}$$

$$G_{IC} = 170.82 + 17.299(a - a_0) - 0.087(a - a_0)^2 \tag{4}$$

To further understand the similarities and differences of fibre bridging in quasi-static and fatigue delamination, the experimental data shown in Figs. 2 and 5 are compared in Fig.7. For the 32-Layer tests, fatigue delamination resistance is much lower than the corresponding quasi-static data during the entire delamination tests. This demonstrates that more fibre bridging can be present in quasi-static delamination growth. The same phenomenon is also observed for the 48-Layer tests before fibre bridging becomes saturation. However, one should note that no obvious difference in delamination resistance is found at the plateau state, indicating the same amount of fibre bridging. In addition, the lengths of fibre bridging region become longer in fatigue delamination compared to quasi-static for both thickness scales. These results, shown in Fig.7, demonstrate that the loading regime not only affects the significance of fibre bridging, but also the length of fibre bridging region.

4.2.2 The Paris representation of fibre-bridged FDG

All fatigue delamination data were first interpreted with the Paris relation and summarized in Fig.8 (a)-(c). The determined Paris resistance curves of each laminate thickness significantly decrease shift from left to right with the increase in length of the fatigue pre-cracks (i.e. the fibre bridging development). This means that the *SERR* required for a given crack growth rate *da/dN* is not constant, but depends on crack extension a-a_0. With crack growth, more bridging fibres can be present in the wake of a crack front, resulting in more strain energy being cyclically stored and released in them and artificially contributing to a higher value of the *SERR*. Similar to quasi-static delamination, there is a plateau state in fatigue delamination. In this state, fibre bridging reaches saturation, leading to the final convergence of the fatigue data in the most right region of the resistance graphs as illustrated in Fig.8.

Referring to the results shown in Figs. 5 and 8, one can reasonably expect that fatigue delamination in 32-Layer and 48-Layer laminates with the same short fatigue pre-crack and at the plateau state should be the same or at least similar, as the amount of fibre bridging in these stages remains the same or similar. Fatigue results with the same short pre-crack (a-a_0 is around 20mm) and at the plateau state are therefore compared in Fig.9 to verify this. As expected, fatigue delamination behaviors in both stages look the same, regardless of thickness increase. These results can provide extra evidence on the correctness of the conclusions made according to Fig.5.

According to the quasi-static and fatigue R-curves illustrated in Fig.7, more fibre bridging can be present in quasi-static delamination growth. With consideration of the obvious decrease shift phenomenon observed in Fig.8, it is reasonable to deduce that fatigue delamination with fatigue pre-crack should locate on the left side of the corresponding data with the same quasi-static pre-crack. To verify this as well as to provide solid evidence to support the conclusions made according to Fig.7, 32-Layer DCB specimens with the same quasi-static and fatigue pre-cracks (i.e. a-a_0=10.0mm) were fatigue tested under the same stress ratio R=0.5. The obtained fatigue data are interpreted via the Paris relation and summarized in Fig.10. As expected, fatigue delamination with the quasi-static pre-crack is much slower than that with the fatigue pre-crack. As fibre bridging is the main reason for the decrease shift of the Paris resistance curves, these data clearly demonstrate that more fibre bridging can be generated in quasi-static delamination than in fatigue case, which is in line with the conclusions made according to Fig.7.

4.2.3 Fatigue data interpreted with the modified Paris law

The use of an appropriate similitude parameter is an important issue in fatigue delamination studies [1,4,6,7,22,23,26]. For fibre-bridged fatigue delamination, the use of the Paris law is only a phenomenological way to interpret the data as well as to qualitatively evaluate the significance of fibre bridging [20,26]. According to the energy principles and fractography results [25,26,29], it was reported that fibre bridging indeed had little contribution to permanent energy release in most cases of a fatigue delamination. Particularly, most damage evolution was actually concentrated on crack front regardless of fibre bridging, making the *SERR* applied on crack front closely related to fatigue crack growth. Accordingly, a modified Paris relation, see Eq.(2) with a new similitude parameter $\Delta\sqrt{G_{eff}}$, has been proposed to determine fatigue delamination behaviors with fibre bridging [26].

To appropriately explore the effects of fibre bridging on fatigue delamination behaviors in multidirectional composite laminates with various thickness scales, all fatigue data illustrated in Fig.8 were re-analyzed via the modified Paris relation and expressed in terms of *da/dN* against $\Delta\sqrt{G_{eff}}$ as illustrated in Fig.11. In contrast to the significant decrease shift phenomenon observed in Fig.8, all fatigue data locate in a relatively narrow band region, regardless of fibre bridging (even though some scatter is observed in Fig.10(b) for only one data set a-a_0=11.35mm for some unknown reason). This clearly suggests that there is a strong correlation between fatigue crack growth *da/dN* and $\Delta\sqrt{G_{eff}}$. As a result, a single power law resistance curve can be reasonably well fitted to determine fatigue delamination with different amounts of fibre bridging, which meets the basic requirement of similitude principles very well. On this point, one can make a tentative conclusion that fibre bridging indeed has negligible effect on FDG behaviors, if the similarity is appropriately represented.

To further investigate thickness effects on fibre-bridged FDG behaviors, all fatigue data illustrated in Fig.11 (excluding the outliner shown in Fig.11(b)) are summarized in Fig.12. Interestingly, fatigue data derived from DCB specimens with different thickness scales overlap each other very well. This means thickness has negligible effect on the fibre-bridged fatigue delamination of multidirectional composite laminates. As a result, a master resistance curve can be fitted to determine fatigue delamination behaviors in multidirectional composite laminates with extensive fibre bridging.

According to the results illustrated in Figs. 11 and 12, one can therefore make an important conclusion that when there is extensive fibre bridging it appears that, if the similarity in FDG is well represented, neither fibre bridging nor laminate thickness has effect on fatigue delamination behaviors.

According to the Paris interpretation of fatigue data illustrated in Fig.8, the obtained Paris resistance curves can significantly shift with crack growth. As a result, as remarked in literature [20], it is inappropriate to use a single resistance curve to determine fatigue delamination behaviors as well as to life a composite structure. The use of a single curve can result in either underestimation or overestimation result, upon on the significance of fibre bridging. However, the use of the modified Paris relation in fatigue data analysis can result in a master resistance curve in determining fatigue delamination behaviors, for cases where there is extensive fibre bridging. This can provide significant convenience for engineering applications where extensive fibre bridging is expected. In addition, one should note that the use of this modified

Paris relation can lead to a decrease in the magnitude of the exponent. A larger value of this parameter indicates that there is strong sensitivity between the applied loads and fatigue crack growth. As a result, a small uncertainty in the loading evaluation can result in severe error in *da/dN* prediction, which should be avoided in engineering design. The use of the modified Paris relation mitigates this sensitivity and, therefore, can improve the accuracy in determining fatigue crack growth as well as lifing a composite structure.

It is worth highlighting that the use of the modified Paris relation in fatigue data interpretation indeed determines FDG behaviors free of fibre bridging. In a recent study [30], a novel methodology based on statistical analysis has been proposed to determine an “upper-bound” FDG curve, which represents fatigue delamination with no or very little bridging retardation and takes inherent data scatter into account. Fig. 13 provides a comparison between the upper-bound given in [30] as well as the experimental data interpreted via Eq.(2) in present study. As expected, the upper-bound FDG curve slightly locates on the left side of these experimental data, indicating a faster crack growth. The results given in Fig.13, therefore, can provide evidence on the validation of employing the methodology provided in [30] to determine a conservative FDG curve. As discussed in literature [30], this conservative curve can be used for material development, characterization and comparative studies, and for composite structural design and lifing studies.

5. Conclusions

The significance of fibre bridging and delamination behaviors in multidirectional composite laminates under quasi-static and fatigue loading are experimentally investigated. For quasi-static experiments, more fibre bridging can be generated in a thinner laminate compared to a thicker laminate, making the magnitude of the experimentally determined *R*-curve dependent on laminate thickness. For FDG, the significance of fibre bridging is dependent on the thickness scale as well, except at a short crack extension and the plateau state. The amount of fibre bridging is related to loading regimes and more bridging fibres can be present in quasi-static delamination growth.

It worth noting that delamination resistance keeps increase with the increase in crack length until it converges into a maximum value, due to the presence of fibre bridging in the wake of the crack front. The change in laminate thickness can dominate or affect the convergence rate of delamination resistance. Particularly, the delamination resistance increases faster in a thinner laminate and the length of fibre bridging region can fully develop sooner. The thickness effects on delamination resistance mainly attribute to the difference in the growth rate and size of fibre bridging region. The considerable fibre bridging and its dependence on laminate thickness are responsible for the influence from specimen geometry.

The application of the modified Paris relation demonstrates that fibre-bridged fatigue data derived from multidirectional composite laminates with different thickness scales can converge into a relatively narrow band region. As a result, a master resistance curve can be reasonably well fitted to determine all fatigue delamination data. Thus, it is reasonable to draw a conclusion that neither thickness nor fibre bridging indeed has obvious effect on fatigue delamination behaviors, if the similarity is appropriately represented.

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Figures

(a) (b)

Fig. 1. Quasi-static and fatigue experimental setups (a) Quasi-static experimental setup; (b) Fatigue experimental setup.

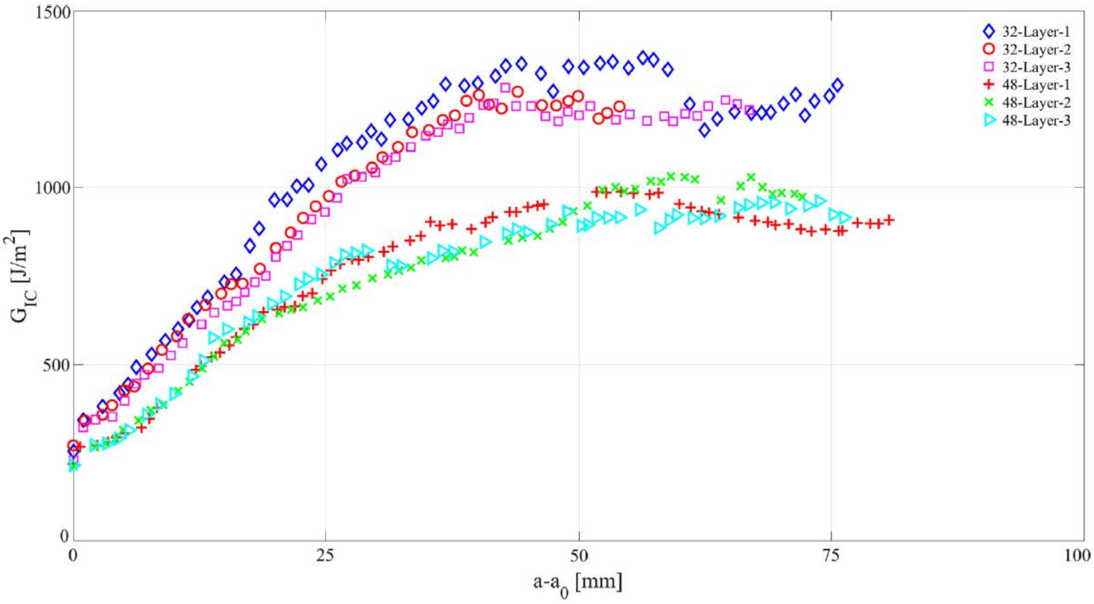
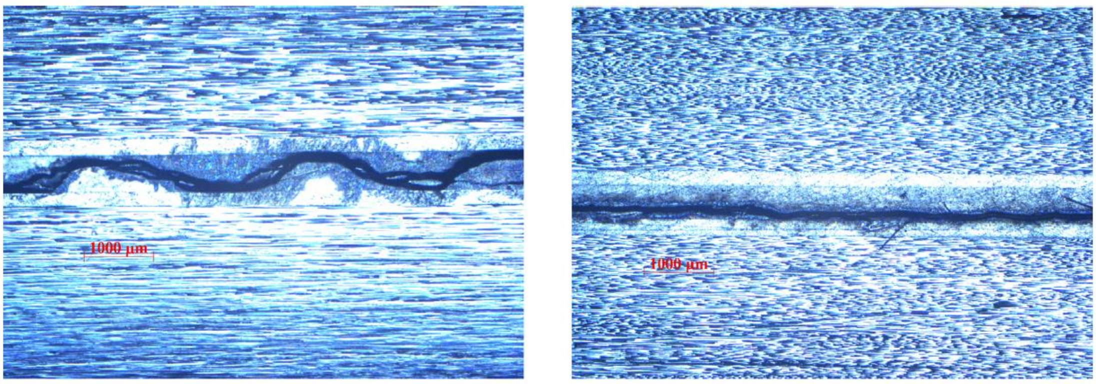


Fig. 2. Quasi-static delamination resistance increase.



(a) (b)

Fig. 3. Quasi-static crack profiles in multidirectional composite laminates (a) 32-Layer; (b) 48-Layer.

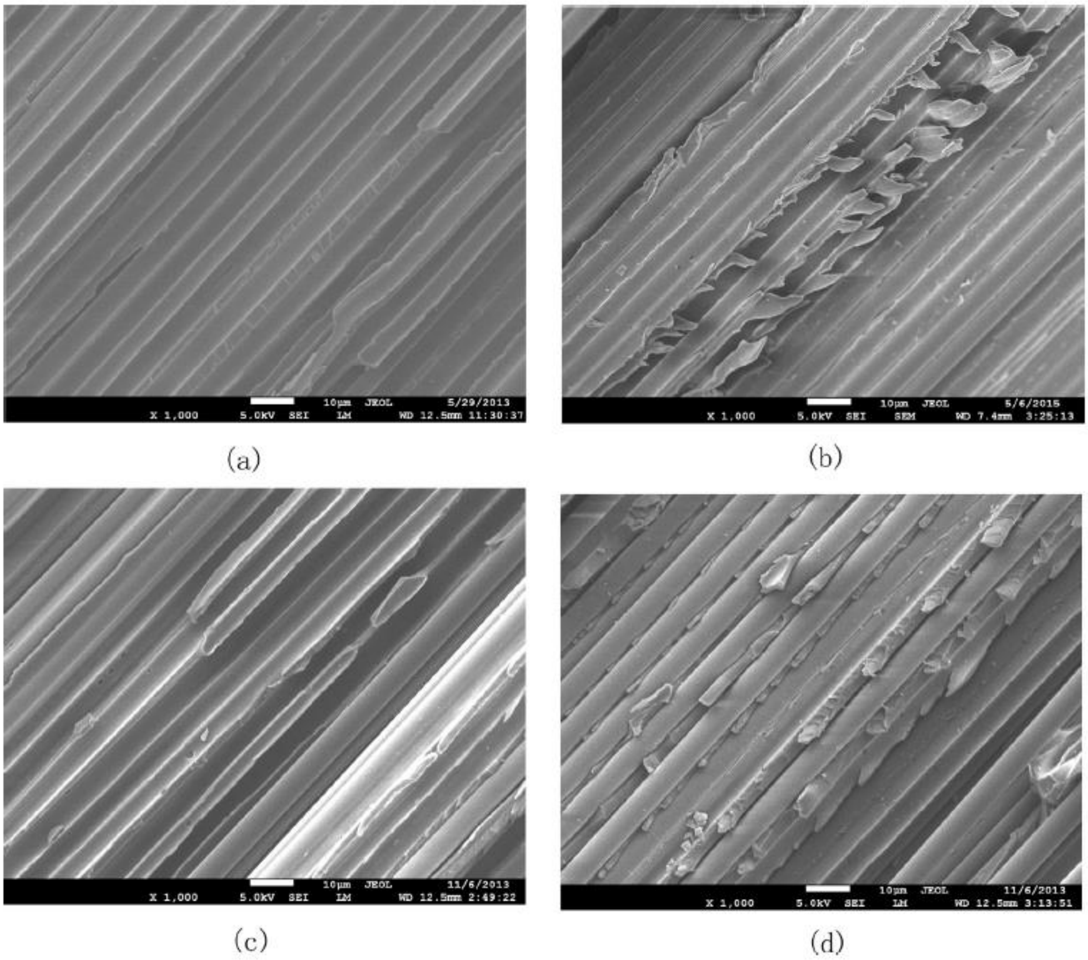


Fig. 4. SEM observations of quasi-static fracture surfaces (a) Onset delamination stage of 32-Layer; (b) Delamination propagation stage of 32-Layer; (c) Onset delamination stage of 48-Layer; (d) Delamination propagation stage of 48-Layer.

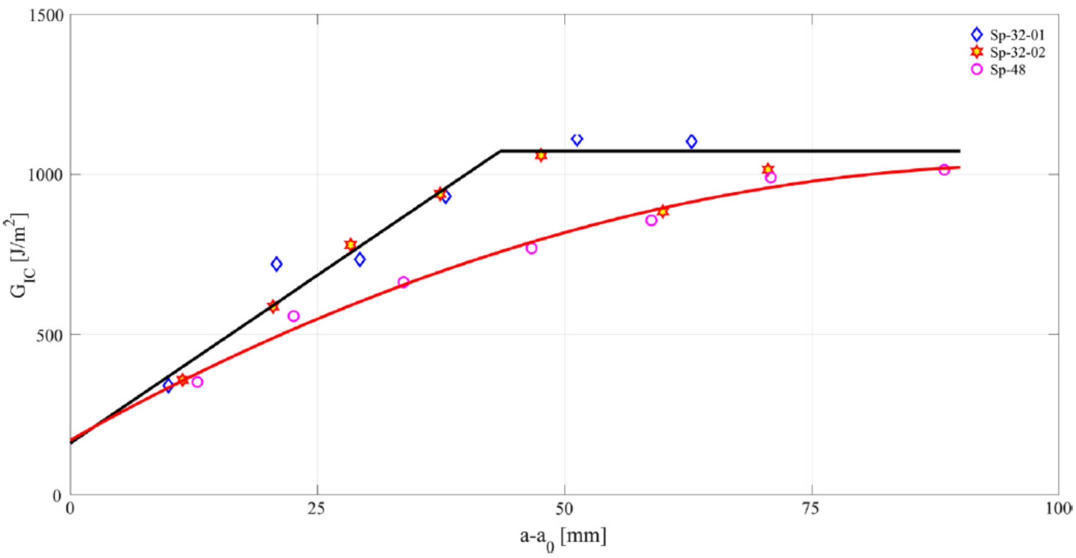


Fig. 5. Fatigue delamination resistance increase.

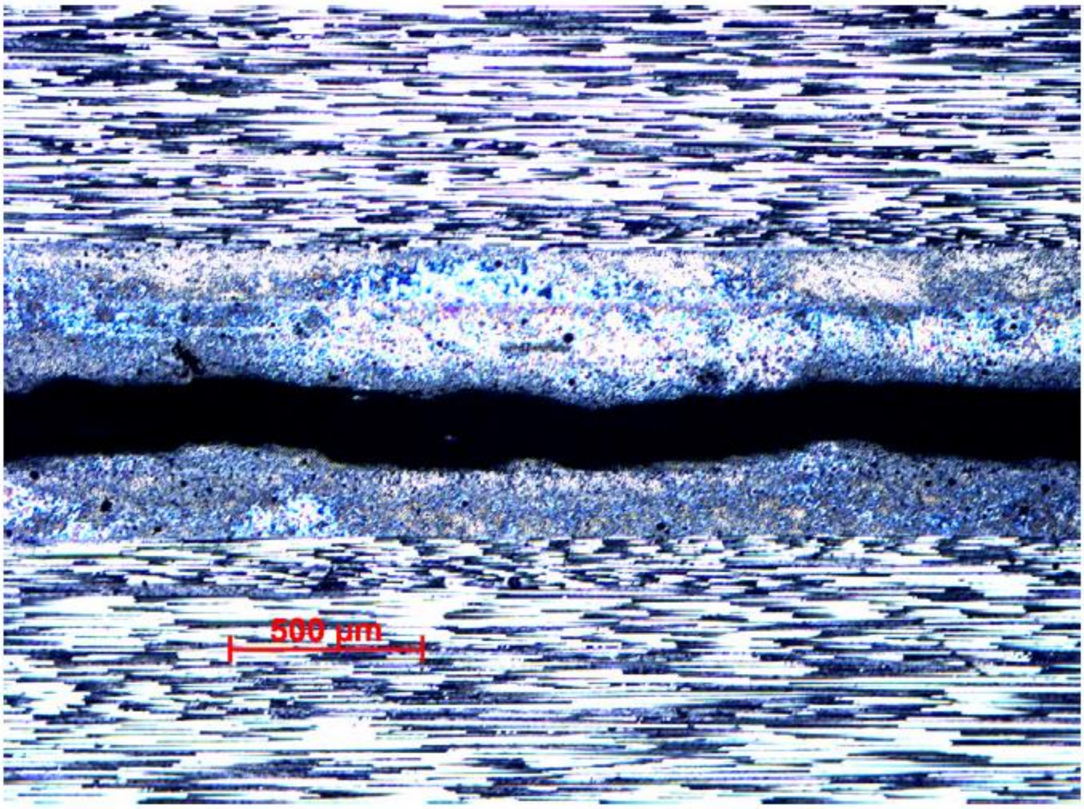


Fig. 6. Fatigue crack profile of multidirectional composite laminates with 32 layers.

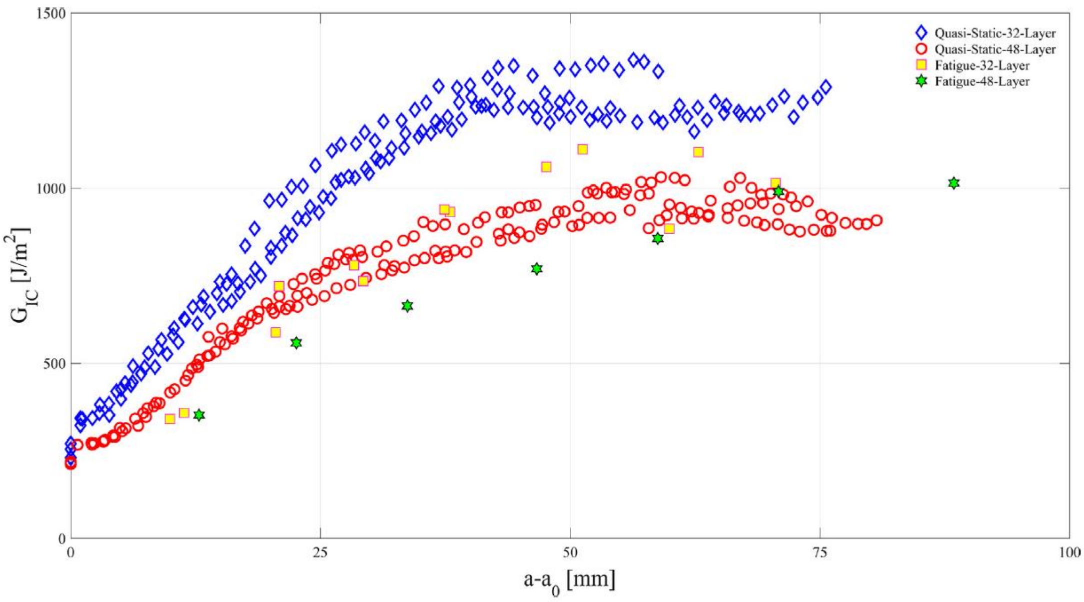
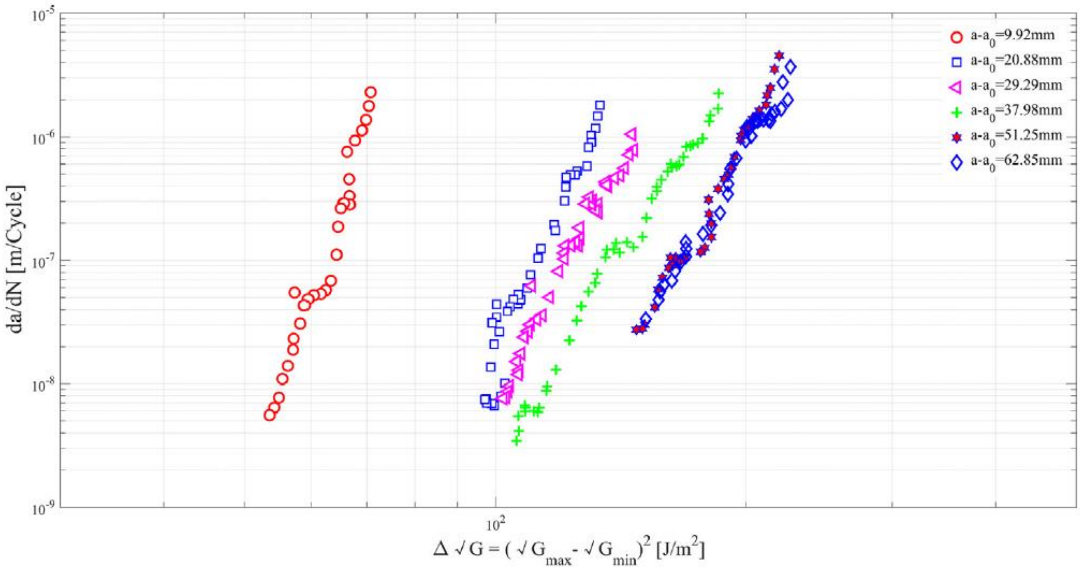
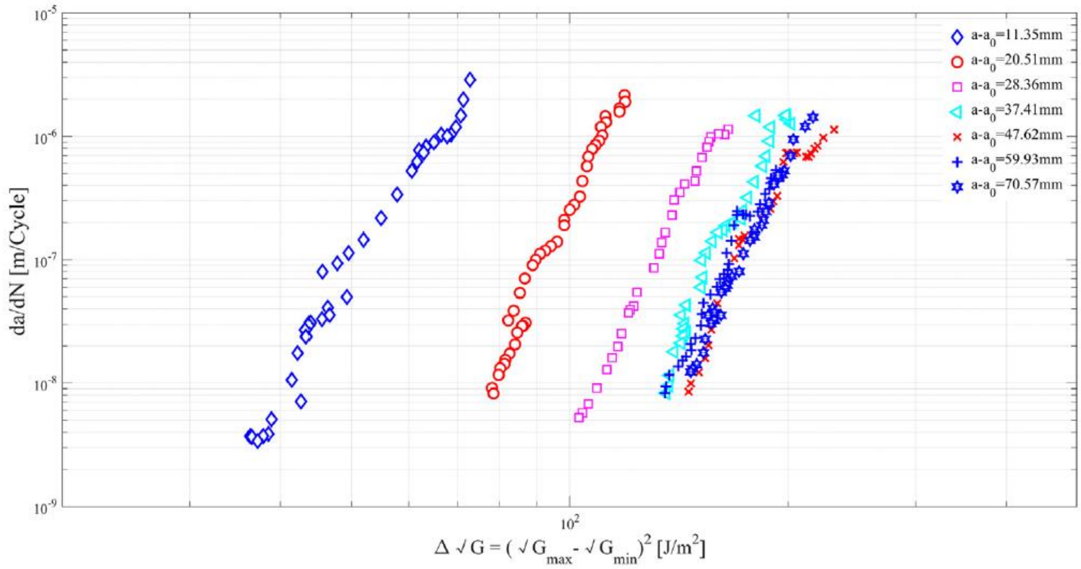


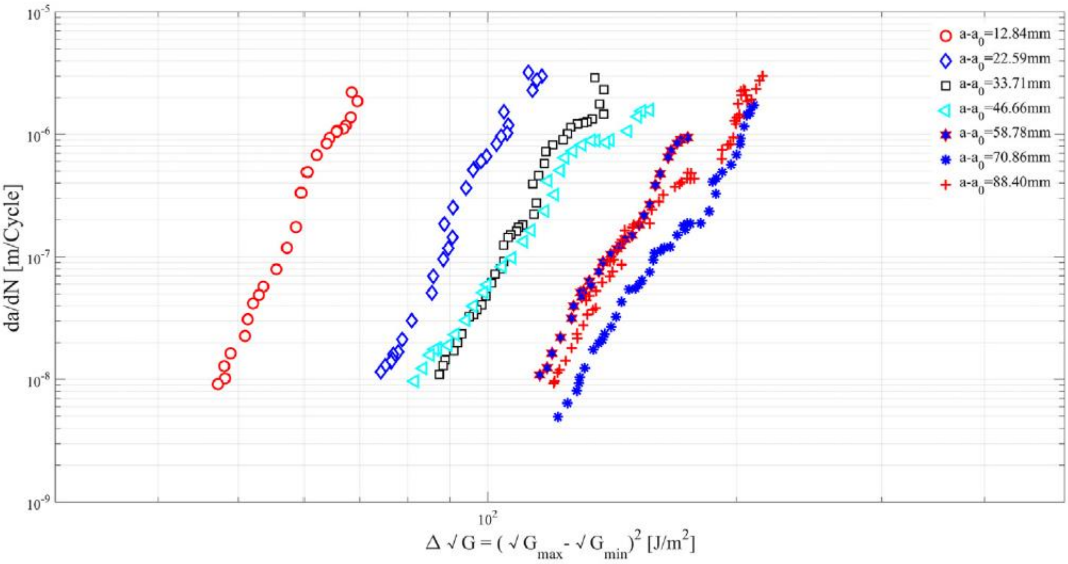
Fig. 7. Quasi-static and fatigue R-curves.


a-a0=9.92mm
a-a0=20.88mm
a-a0=29.29mm
a-a0=37.98mm
a-a0=51.25mm
a-a0=62.85mm
da/dN [m/Cycle]
Δ √G = (√G max - √G min)2 [J/m2]

(a)

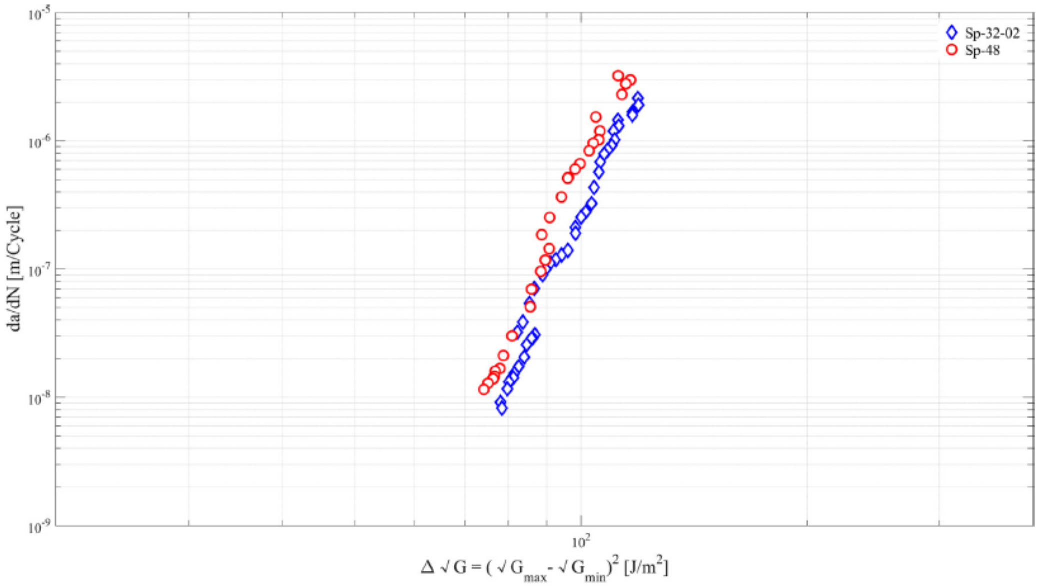

a-a0=11.35mm
a-a0=20.51mm
a-a0=28.36mm
a-a0=37.41mm
a-a0=47.62mm
a-a0=59.93mm
a-a0=70.57mm
da/dN [m/Cycle]
Δ √G = (√G max - √G min)2 [J/m2]

(b)

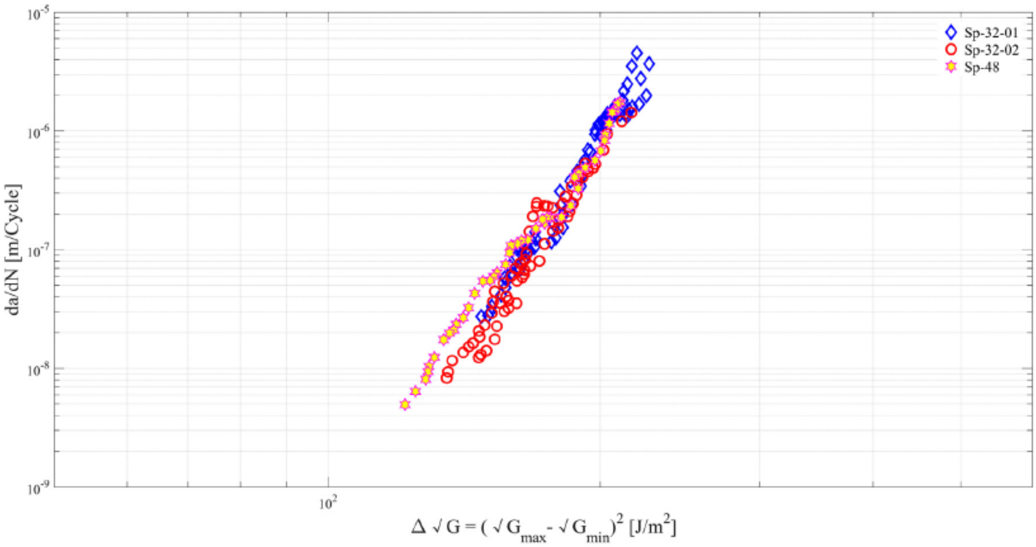


(c)

Fig. 8. The Paris representation of fatigue delamination with fibre bridging (a) Sp-32-01; (b) Sp-32-02; (c) Sp-48.



(a)



(b)

Fig. 9. The significance of fibre bridging in FDG (a) a-a0 is around 20 mm; (b) Plateau state.

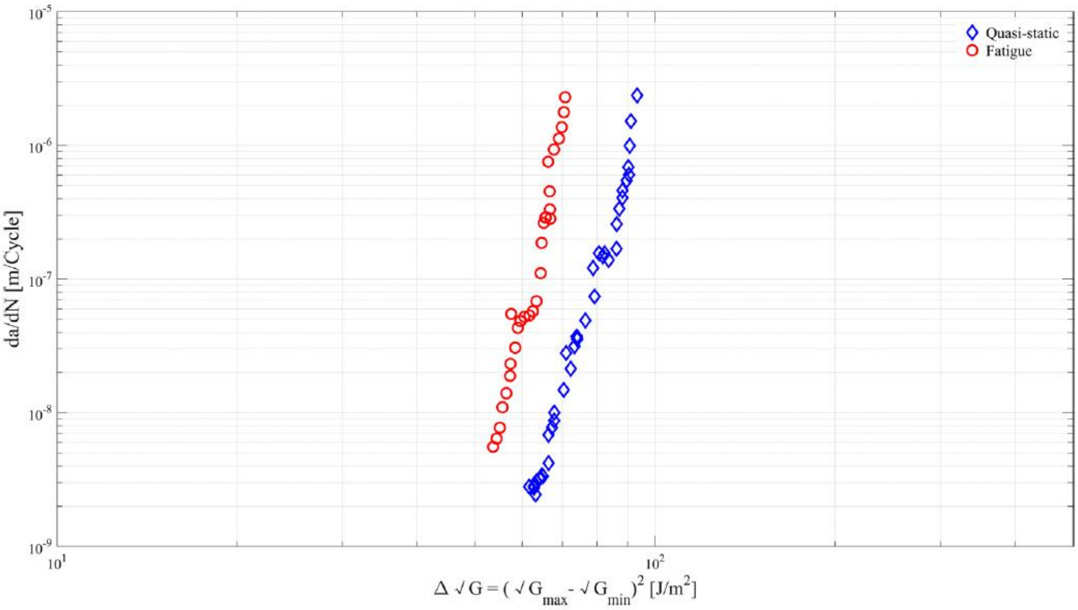


Fig. 10. The difference of fibre bridging in quasi-static and fatigue delamination.

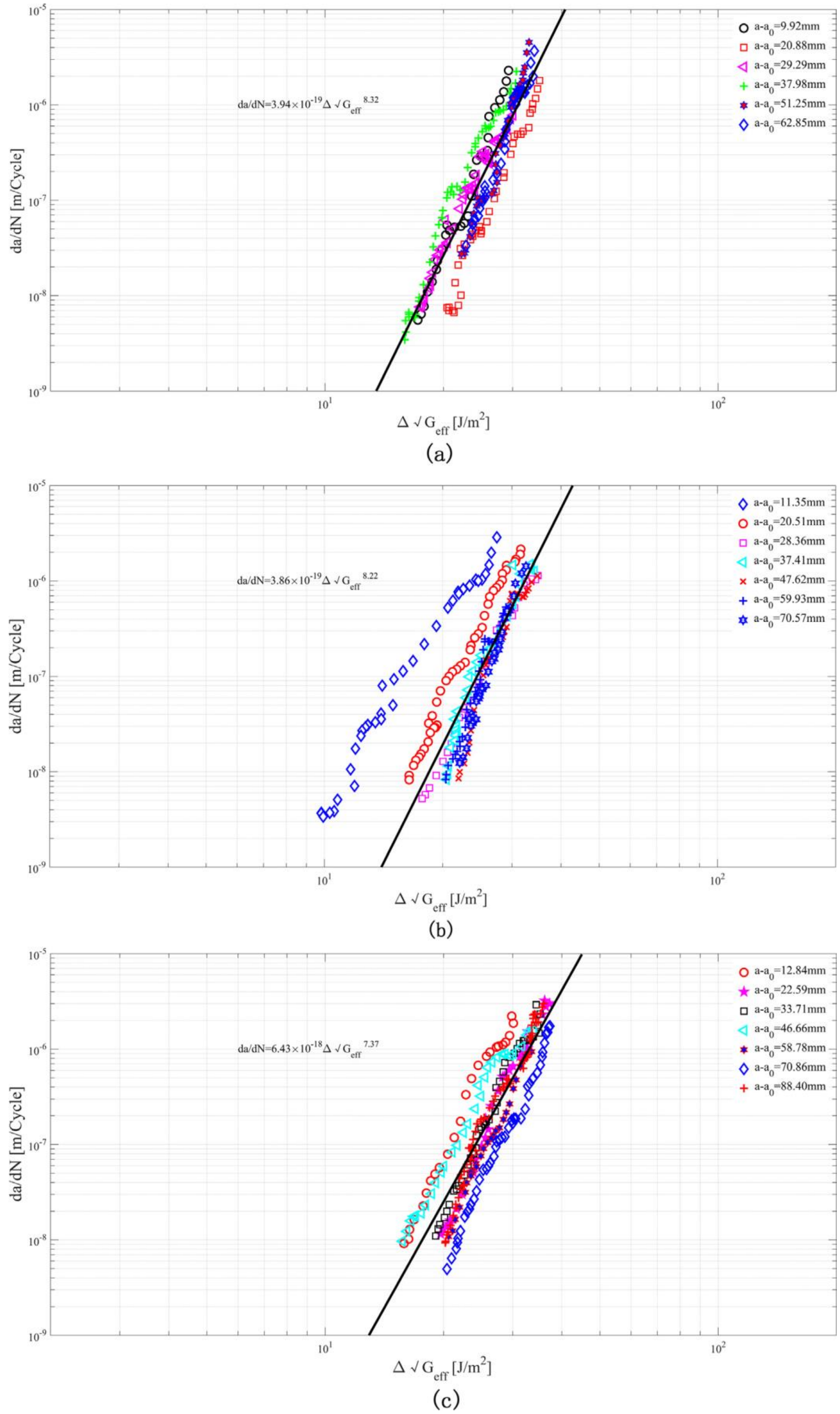


Fig. 11. Fatigue delamination interpreted via the modified Paris relation (a) Sp-32-01; (b) Sp-32-02; (c) Sp_48.

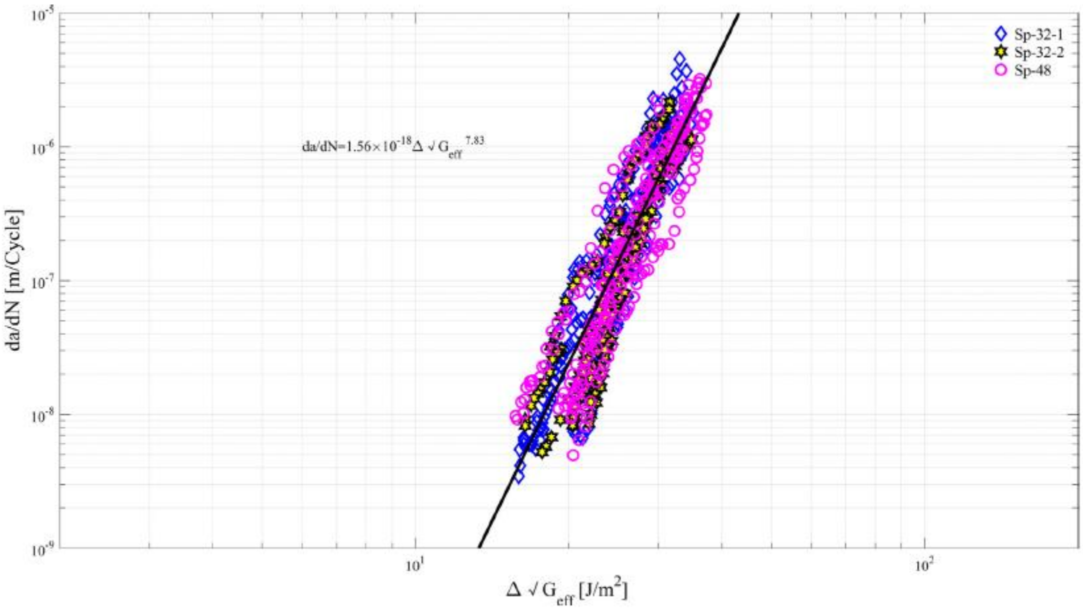
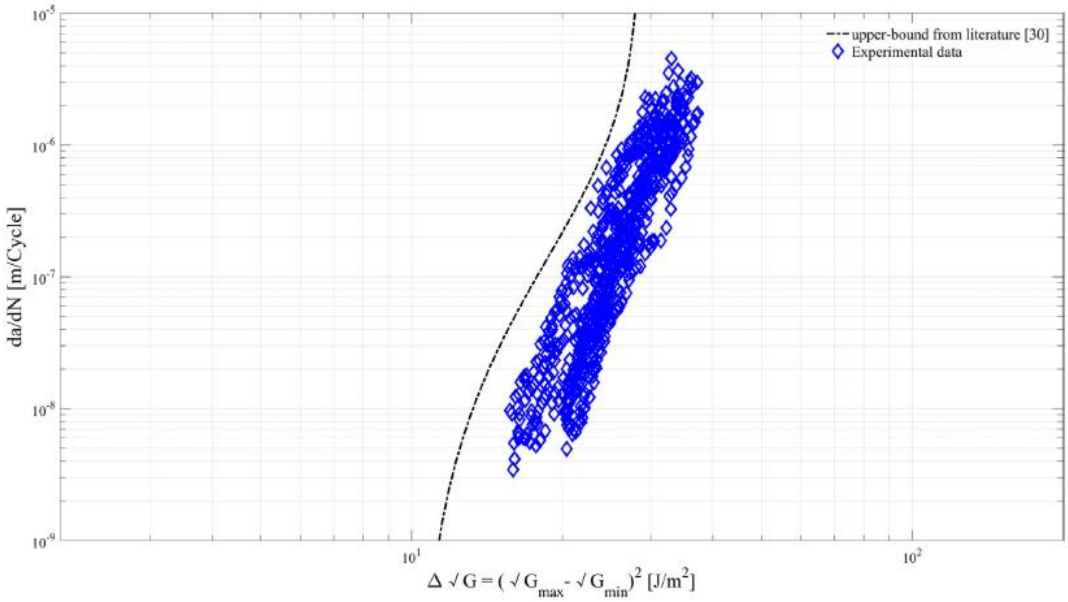


Fig. 12. Fibre-bridged fatigue delamination in multidirectional composite laminates.



A comparison between the upper bound FDG curve calculated via the methodology proposed in literature [30] and the experimental data interpreted via the modified Paris relation.

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Fibre-bridged fatigue delamination in multidirectional composite laminates

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